Commun Nonlinear Sci Numer Simulat 44 (2017) 89–107

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

journal homepage: www.elsevier.com/locate/cnsns

Research paper

Flow switchability of motions in a horizontal impact pair with dry friction

Yanyan Zhang, Xilin Fu*

School of Mathematical Sciences, Shandong Normal University, Ji'nan, 250014, PR China

ARTICLE INFO

Article history:
Received 24 January 2016
Revised 15 June 2016
Accepted 18 July 2016
Available online 30 July 2016

Keywords:
Horizontal impact pair
Dry friction
Flow switchability theory
Stick motions
Grazing motions

ABSTRACT

Using the flow switchability theory of the discontinuous dynamical systems, the present paper is to develop mechanical complexity in a periodic-excited horizontal impact pair with dry friction. The impact pair studied models the motions of a single bolted connection which is vibrated in the plane perpendicular to the bolt axis. According to motion character, the phase space can be partitioned into several domains and boundaries, in which a continuous dynamical system is defined in each domain, and it possesses dynamical properties different from its adjacent subsystem, the boundaries have different properties and can fall into two kinds – displacement boundaries and velocity boundaries. In this paper, using G–functions defined on separation boundaries to study flow switching on corresponding boundaries, the analytical switching conditions on each boundary are developed: the sufficient and necessary conditions of occurrence and disappearance of sliding-stick motion and side-stick motion are obtained, the sufficient and necessary conditions of grazing motion appearing on velocity boundaries are also obtained, and the analytical conditions of appearance for grazing motion on displacement boundaries are preliminarily discussed. Thus it can be seen that dynamical behaviors of the horizontal impact pair with or without dry friction are essentially different, in particular flow switchability on displacement boundaries depend on whether the conditions of passable flows on velocity boundaries are satisfied. The numerical simulations are given to demonstrate the analytical results of two stick motions and grazing motions in such pair. More details of the motions for the object reaching the intersection point of displacement boundary and velocity boundary need to be considered further in the future.

1. Introduction

Impact and friction are universal in mechanical engineering, and are the common and important contacts between two or more dynamical systems. Modeling of impact or friction in practical problems and research on their dynamical behaviors can provide information for using or controlling them. The dynamical systems derived from impact or friction have been extensively studied not only due to their universality, but also because of their strongly nonlinear, discontinuous and complex dynamical behaviors.

Whenever the clearance or gaps exist in machinery, the impacts take place. To use or decrease the effect of impacts, the dynamical behaviors of the impact oscillators were widely studied. Using a difference equations, Holmes [1] studied

* Corresponding author.
E-mail address: xilinfu@gmail.com (X. Fu).

http://dx.doi.org/10.1016/j.cnsns.2016.07.015
1007-5704/

periodic motions and chaotic motions of a ball bouncing on a periodically excited table. In Heiman et al.[2], the steady state 2:1 motions and the corresponding stability for an inclined impact pair were studied by return map. Bapat and Bapat [3] investigated the dynamical behaviors of a horizontal impact pair under periodic displacement excitation, and obtained the stability regions of the periodic motion with two symmetrical impacts theoretically and numerically. Introducing discontinuities into discrete time Poincare maps, Foale and Bishop [4] investigated the complex motions of forced systems with impacts. A horizontal impact pair under sinusoidal displacement excitation was studied by Poincare mapping structure in Han et al. [5], period-1 motion with symmetrically alternative impacts was investigated in greater detail. Cheng and Xu [6] investigated the Hopf bifurcations of periodic motions with one impact under resonance cases in a two-degree-of-freedom vibro-impact damper system. Zhang and Fu [7] developed the analytical conditions to predict periodic motions in an inclined impact pair using discrete mapping theory of discontinuous dynamical systems.

Friction can exist wherever two or more moving parts contact each other, which derives a non-smooth and strongly nonlinear systems. For a mass-spring-dashpot with dry friction, Shaw [8] studied its periodic motion with or without sticking and corresponding stability using bifurcation theory. A non-smooth friction oscillator under self- and external excitation were investigated in Hinrichs et al. [9], the bifurcation behaviors were predicted using numerical simulations and experimental method. Ko et al. [10] studied the dynamics of a mass-damper-spring frictional system with or without disturbance theoretically and experimentally. The dynamical behaviors of a block-on-belt system with spring and harmonically external force were investigated in Cheng and Zu [11], the complex behaviors characterized by periodic, quasi-periodic and chaotic attractors were studied using numerical simulations. Pascal [12] studied the dynamics of a two-degree-of-freedom oscillator under dry friction, and obtained two families of periodic motions using analytical method. Using Fourier expansion and iteration perturbation method, Eigoli and Vossoughi [13] obtained an accurate analytical solution of vibrations of strongly nonlinear friction drive robots.

For above systems, the effect of impact and friction were discussed independently, but impact and friction often presented at the same time in mechanical engineering. So it was not enough to independently study the dynamical behaviors of the impact oscillator or the friction-induced oscillator. Chin et al. [14] investigated several kinds of grazing bifurcations in a periodically forced impact oscillator with the addition of friction using Nordmark map. Bapat [15] studied the N-impact-per-cycle periodic motions in an inclined impact damper with friction by theoretical predictions and numerical simulations. Periodic motions of an impact oscillator in the presence of dry friction were investigated in Cone and Zadoks [16], the corresponding stability and bifurcations were developed by numerical simulations. The dynamic response of a revolute joint in a four-bar mechanism with a clearance was discussed in Rhee and Akay [17], periodic motions of a pin were given using Poincare maps. Blazejczyk-Okolewska [18] investigated the bifurcation diagrams of an impact oscillator with external periodic force and dry friction by numerical analysis. For a rigid-body mechanisms with impact and friction in Burns and Piiroinen [19], the Brach impact mapping and an energetic impact mapping were investigated, and the results of two mappings were compared using a slender rod as a model example.

The above results on impact and friction mainly discussed the dynamics of mentioned systems, but did not study their motions switching, so the complexity of dynamical behaviors cannot be fully investigated. In recent years, the theory of the discontinuous dynamical systems, which regards the domains and boundaries where impact or friction occur as time-dependent, was initially formed. The phase space of the discontinuous dynamical systems was partitioned into several subdomains and boundaries in Luo [20], various fundamental flows passability and their decision theorems were given. Using this theory, Luo and Gegg [21] gave the sufficient and necessary conditions of grazing motions and stick motions in a periodically forced dry-friction oscillator, and illustration of special motions were carried out. Furthermore Luo [22,23] introduced $G-$functions on discontinuous boundaries for the discontinuous dynamical system to study motion complexity, and the flows passability and switching bifurcations were classified. A simplified brake system under periodic excitation was investigated in Luo [24], periodic motions and local stability were analytically predicted by mapping structure. Luo [25] developed the flow switchability theory of the discontinuous dynamical systems on time-varying domains, and applied such theory to different systems modeling practical problems. The analytical prediction of periodic motion in a horizontal impact pair under a periodic displacement excitation was presented in Guo and Luo [26], switching bifurcations and chaos were carried out. Luo and Huang [27] developed the analytical condition of flow switchability in a non-linear, friction-induced, periodical force oscillator. Using the theory of the discontinuous dynamical system, bouncing ball systems, horizontal impact pair and a generalized Fermi-acceleration oscillator were discussed in Luo and Guo [28], the analytical prediction of periodic motion with or without stick and corresponding stability analysis in these oscillators were developed.

From above discussions, using the theory of the discontinuous dynamical systems, the dynamical behaviors of the impact oscillator or the friction-induced oscillator were sufficiently investigated, but the researches on the dynamical systems influenced by impact and friction simultaneously were relatively less, particularly few articles discussed the flow switchability. In this paper, the switching mechanism in a periodic-excited horizontal impact pair with dry friction are investigated using the flow switchability theory of the discontinuous dynamical systems. This impact pair studied models the motions of a single bolted connection which is vibrated in the plane perpendicular to the bolt axis. According to the occurring of impact and the direction of friction, the phase space can be divided into several domains and their boundaries, and these boundaries can fall into two categories due to their different properties - displacement boundaries and velocity boundaries. And based on such domains and boundaries, the behaviors of the object can be classified into four cases: slipping, impacting, slide-sticking due to dry friction and side-sticking due to limited clearance. By studying the flow switching on the boundaries of two adjacent domains, the sufficient and necessary conditions for the occurring and vanishing of two stick motions